Cyclic Plastic Deformation Characteristics of Subgrade under Moving Train Wheel Load

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ABSTRACT

Cyclic plastic deformation of subgrade and other engineered layers is generally not taken into account in the design of railway bridge transition zones, although the plastic deformation is the governing factor of frequent track deterioration. Actual stress behavior of fine grained subgrade/embankment layers under train traffic is, however, difficult to replicate using the conventional laboratory test apparatus and techniques. A new type of torsional simple shear apparatus, known as multi-ring shear apparatus, was therefore developed to evaluate the actual stress state and the corresponding cyclic plastic deformation characteristics of subgrade materials under moving wheel load conditions. Multi-ring shear test results has been validated using a theoretical model test results; the capability of the multi-ring shear apparatus for replicating the cyclic plastic deformation characteristics of subgrade under moving train wheel load conditions is thus established. This paper describes the effects of principal stress rotation (PSR) of the subgrade materials to the cyclic plastic deformation in a railroad and impacts of testing methods in evaluating the influence of principal stress rotation to the track deterioration of rail track.

Keywords: subgrade, cyclic plastic deformation, moving wheel load, multi-ring shear apparatus, principal stress rotation

1 INTRODUCTION

Frequent track degradation introduced by cyclic plastic deformation accumulation in rail track engineered layers, especially within track transition zones, where the track stiffness intensely changes within a short distance is a significant technical problem to the rail industry. Conventional design guidelines provide insignificant attention to plastic deformation of railroad engineered layers under moving traffic [1]. Conventional loading experiments; cyclic tri-axial, cyclic direct shear, and Californian bearing test used in these design guidelines are not appropriate to simulate the actual stress states inside the subgrade under moving wheel loads, where the principal stress axis rotation is a predominant factor of the deformation characteristics of rail track.

Presence of principal stress axis rotation in the laboratory experiments produces actual traffic conditions under the moving wheel loads, where the stress state of a given element in a subgrade changes with the location of the wheel [2]. As triaxial or single point load test cannot achieve rotation of the stress state with time, Momoya, Sekine [3] and Hirakawa, Kawasaki [4] performed scale down model test series to evaluate the behavior of subgrade under moving loading and proved that a single point loading has less capability to replicate real deformation characteristics of a rail track. Higher cost, and difficulties to control loading pattern in model tests highlight requirement of a simple laboratory element test method to replicate the actual loading conditions of fine grained subgrade in a rail track under moving wheel load.

This study therefore developed a new type of torsional simple shear apparatus, known as multi-ring shear apparatus, which was proved suitability to replicate stress state of layers with only coarse material under moving load [5, 6]. The capability of multi-ring shear apparatus to replicate the actual cyclic stress-strain characteristics of rail track subgrade subjected to moving wheel load is presented in this study including the model test results of Momoya, Sekine [3].

2 TESTING METHOD

Momoya, Sekine [3] performed a model test series to investigate the influence of deformation characteristics of rail track ballast layer and subgrade under moving wheel loads. This study adopted an experimental methodology and the results of this model test series to investigate the cyclic deformation of subgrades under moving wheel loads, using a multi-ring shear apparatus. Since the current multi-ring shear apparatus was originally designed for ballast layers, the apparatus was modified as shown in Figure 1 to accommodate testing of particulate soil layers. Two rubber membranes on both inner and outer sides to prohibit movement of fine particles into small gaps between inner and outer rigid rings and filter papers on both bottom and top porous plates to prevent blocking voids in porous plates by fine particles were introduced to multi-ring shear apparatus.

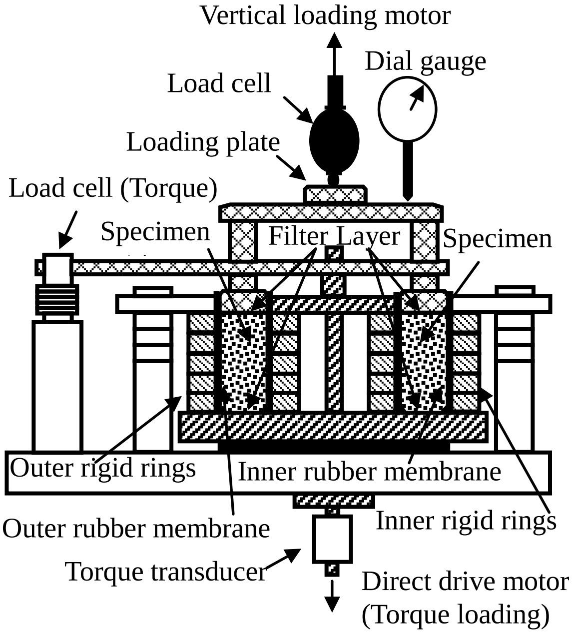

Fig. 1. Modified multi-ring shear apparatus

The width of the specimen is 60mm with 120mm inner diameter and 240mm outer diameter. Sample height for a multi-ring shear test can be varied from 20mm to 100mm. As height of subgrade in the model test was 200mm, this study selected 100mm as sample height to obtain realistic behavior with sample behavior at small scaled model test. Geometry of sample used in multi-ring shear test illustrates in Figure 2. It further shows stress-strain terms and coordinate system used in multi-ring shear test. Similar procedure followed by Ishikawa, Sekineo [6] and Inam, Ishikawa [5] to evaluate vertical stress (σ_a), axial strain (ε_a), shear stress ($\tau_{a\theta}$), and shear strain ($\gamma_{a\theta}$) in multi-ring shear test was used in this study. Lateral deformation of sample was not considered in the experiments performed with multi-ring shear apparatus.

Estimating the behavior of subgrade under moving wheel load is the key aspect of this study, a model test performed only with subgrade and super structure of a railway track was therefore adopted. This study used air-dried Toyoura sand, having relatively uniform gradient by referring model test (Momoya et al., 2005). Specimens were prepared, using three equal layers and initial densities were achieved by tamping with a wooden rammer. Final required dry density; 1560 kg/m^3 for each experiment was obtained after following one-dimensional consolidation. Three different types of experiments; static shear test, cyclic axial load test, and cyclic moving wheel load test can be performed to evaluate deformation-strength characteristics of subgrade, using multi-ring shear apparatus.

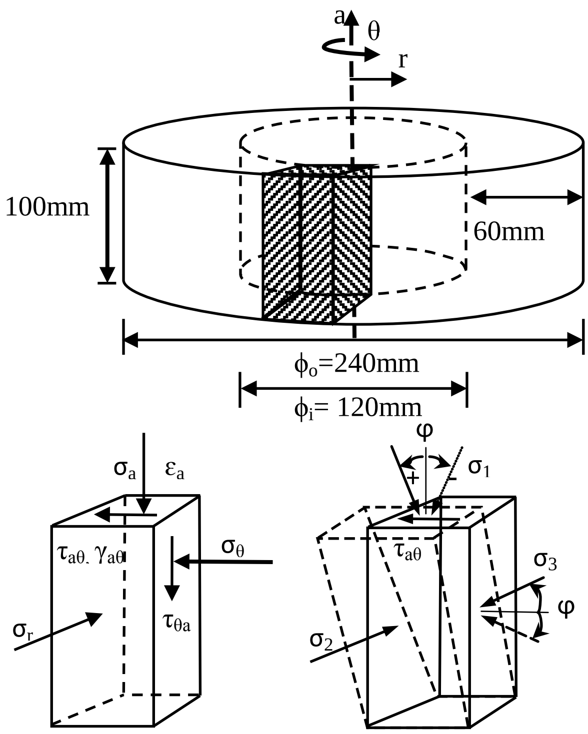

Fig. 2. Stress-Strain definition for soil specimen

In the monotonic shear loading test (static shear test), after one-dimensional consolidation to ensure the dry density was similar to the model test data, the specimen was further consolidated under a controlled stress condition to gain specified vertical stress (σ_a) and then the sample was monotonically sheared at a constant shear strain rate of 0.01 %/min, while the specified vertical stress was kept constant. To replicate cyclic triaxial compression test conditions, cyclic single point loading test (FL test) was performed only with an axial stress in a sinusoidal waveform after consolidation step. To perform moving wheel load test (ML test) in multi-ring shear apparatus, loading history was obtained from the model test presented in Figure 3, where it shows the variation of axial strain and shear strain of subgrade with 37.5kN wheel load under two-way traffic. Maximum vertical stress was 80.12 kPa, while the maximum value of shear stress was ± 13.12 kPa. These variations of the axial stress and the shear stress obtained from Figure 3 were applied in sinusoidal waveforms to consolidated soil specimen as given in Figure 4.

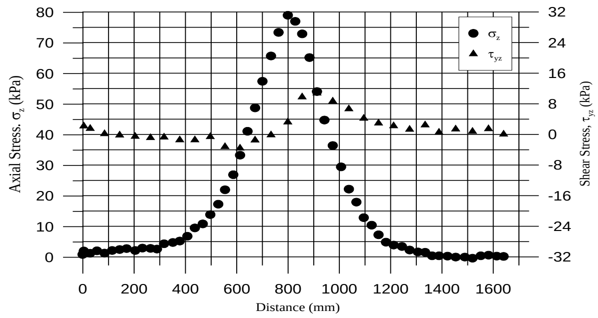

Fig. 3. Rail seat stress-wheel position relationship

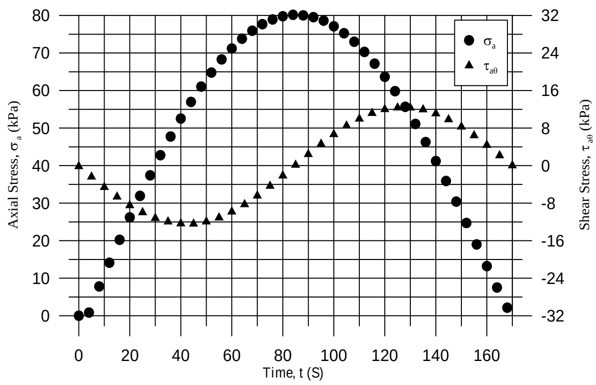

Fig. 4. Moving wheel load in multi-ring shear test

In both ML and FL tests, 100 cycles at 0.006 Hz loading frequency were selected, referring small-scaled model test conditions. As the model test was performed under two-way traffic conditions, shear stress was cyclically applied for bidirectional loading by changing phase angle of 180 degrees for every succeeding loading cycle as mentioned in Inam, Ishikawa [5] multi-ring shear tests. In both cyclic multi-ring shear tests, required axial stress and shear stress were achieved, using 14 pre-loading cycles according to the small-scaled model test conditions.

3 PERFORMANCE OF MULTI-RING SHEAR APPARATUS

3.1 Comparison between multi-ring shear test and model test

To evaluate the capability for replicating response of subgrade under moving wheel load, cyclic plastic deformations of railway subgrade with small-scaled model test and multi-ring shear test were estimated as shown in Figure 5. These results indicate that the ε_a-N_c relations of the model test and the multi-ring shear test have similar response under moving wheel load conditions. The deviation between the two distributions within pre-loading cycles, and the first 25 cycles is not significant as shown in Figure 5. Initial elastic settlement by self-weight of loading plate in multi-ring shear apparatus which cannot be measured using dial gauges, and higher initial permanent deformation in multi-ring shear test within pre-loading cycles, where higher elastic characteristics introduce into multi-ring shear specimens than model tests are key reasons for diversion of the multi-ring shear test results from the model test results, even after following identical test conditions as shown in Figure 5.

In Figures 6 and 7, axial stress-strain relations of the model test and the multi-ring shear test respectively clearly illustrate the triggering factors of such change. Permanent axial deformation of the multi-ring shear test, after pre-loading is nearly 12% higher than the model test data. At early stage of cyclic loading, a large hysteresis loop appears within loading and unloading curves and the residual settlement increases between cycles of both the model test and the multi-ring shear test as Figures 6 and 7. Within increasing cycle numbers, size of these loops and permanent settlement between cycles become small, introducing elastic characteristics to the specimen. Such similar behavior was observed in ballast of rail tracks and unbound base course layers of payment under moving wheel load conditions [5, 6].

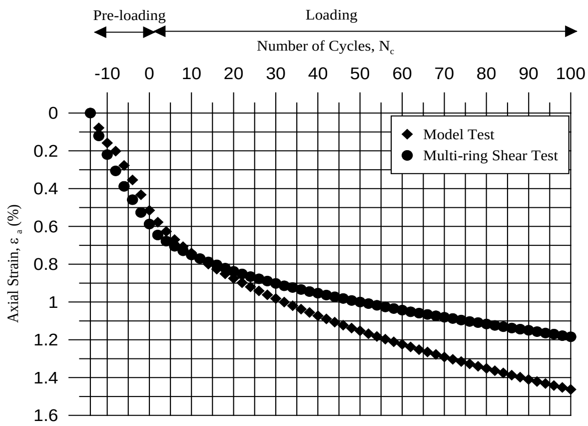

Fig.5. Axial strain distributions under cyclic moving load tests

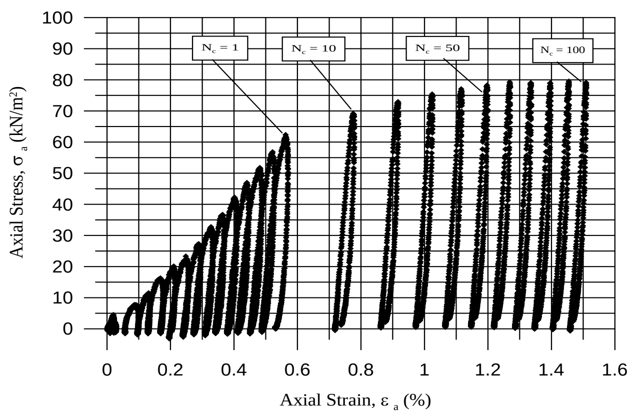

Fig. 6. Axial strain-strain relation of cyclic moving load in small scaled model test

3.2 Influence of loading method

The performance of the multi-ring shear apparatus was further examined with different loading methods. FL test was performed to estimate the effects presence of PSR in a soil element under moving wheel load conditions, since conservative guidelines use only single point loading test methods as cyclic triaxial test and Californian bearing test, by neglecting influence of PSR on subgrade deformation. Figure 8 shows axial stress-strain relation of cyclic single point loading test performed using multi-ring shear apparatus. It indicates that a similar elastic behavior with increasing loading cycles similar to the ML test. FL test however reaches its elastic characteristics rapidly compared to ML test as shown in Figure 7 and 8.

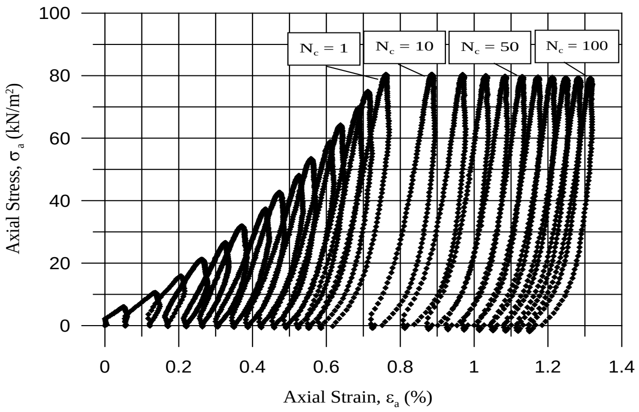

Fig. 7. Axial strain-strain relation of cyclic moving load in multi-ring shear test

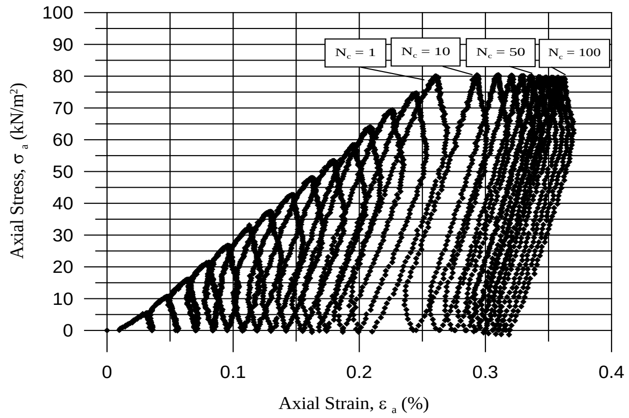

Fig. 8. Axial strain-strain relation of cyclic single point load in multi-ring shear test

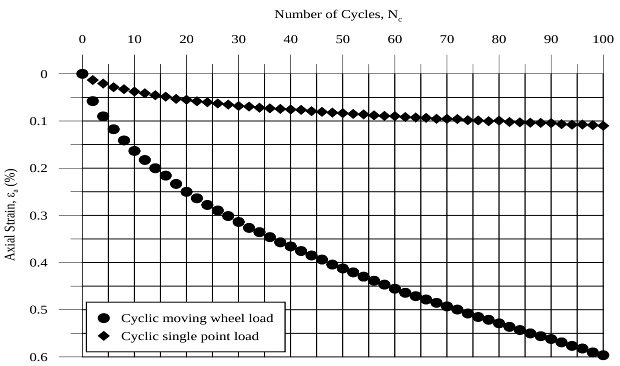

Fig.9. Axial strain variation in cyclic multi-ring shear tests

Figure 9 shows ε_a-N_c relation of single point load and moving wheel load tests of multi-ring shear apparatus after pre-loading cycles. It also indicates that FL test quickly achieves its elastic characteristics than ML test, where slope of distribution of FL test decreases with increasing loading cycles, while the distribution of ML test still shows a higher slope. Permanent axial strain after introducing shear into soil specimen in cyclic moving wheel load test increases by more than 80% of cyclic single point test.

4 CONCLUSIONS

Based on experimental results and discussion, following conclusions are obtained:

1. Modified multi-ring shear apparatus is able to approximately replicate axial stress-strain behavior of subgrade under moving wheel load conditions.
2. Cumulative deformation of subgrade by single load test (FL test) is much smaller than ML test in multi-ring shear test as a result of neglecting principal stress axis rotation under moving wheel load.
3. Principal stress axis rotation by moving wheel load critically impact on residual settlement of subgrade and presence of PSR can replicate actual loading history on rail track subgrade.

All these findings of this study guide to conclude that modified multi-ring shear apparatus has a higher capability to replicate actual stress-strain response of subgrade in rail track under moving train load.

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